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A study of the $Be^9(d, n)B^{10}$ reaction by means of nuclear emulsions

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With 12 figures in the text

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ABSTRACT

The energy distribution of neutrons from the $Be^9(d, n)B^{10}$ reaction for 7 MeV deuterons was studied by means of nuclear emulsions. So far only 90° scattered neutrons have been investigated. The existence of an excited level of about 3.1 MeV roughly confirms the 2.88 MeV level found by Reid and the 2.95 MeV level observed by Génin. Because of the high neutron background from the gold backing for neutron energies below about 4 MeV, the mean measurements have so far been concentrated on neutron energies $\gtrsim 4$ MeV. The energy distribution of neutrons from the $Au(d, n)Hg$ reaction, thick gold target, is given. An equipment for measuring the deuteron-energy distribution of the internal cyclotron-beam by means of nuclear emulsions was constructed and used. The new microscope mechanical object stage described earlier proved to be very useful, making possible more accurate and much faster measurements than before.

1. Introduction

A large number of investigations concerning the energy levels in B^{10} have been carried out. However, despite the comprehensive material already collected, there are still many cases of ambiguities for some levels, not only concerning their properties, but even their existence. Thus Rasmussen, Hornyak and Lauritsen [1], bombarding thick beryllium targets with 1.2 MeV deuterons and investigating the energy of the gamma rays emitted from the residual B^{10}-nucleus, found the interesting feature that a number of the transition energies were integral multiples of 713 keV to an accuracy of the order of 0.5 percent. It was believed that at least the radiation at 713, 1424, 2138 and 3580 keV (corrected for the Doppler shift) corresponded to transitions from excited levels directly to the ground state of B^{10}. As Hornyak, Lauritsen, Morrison and Fowler [2] remark in their survey article, only a true simple harmonic motion can quantum-mechanically have a Fourier analysis containing only integral harmonics. However, in the level scheme given for B^{10}, the levels at 2.713 keV = 1.42 MeV and 4.713 keV = 2.85 MeV are dashed, and in a note added in proof it is pointed out that no neutrons from the $Be(d,n)B$ reaction corresponding to possible levels at 1.4 or 2.8 MeV are observed in a work by Ajzenberg [3]. According to this investigation, levels at 0.71, 1.73, 2.14 and 3.58 MeV would account for all the observed gamma-rays < 3.6 MeV. Hence the 1.42 MeV and the 2.85 MeV levels were not believed to exist and the remaining fact that the energy of the levels at 2.14 MeV and 3.58 MeV are integral multiples of 0.713 MeV might be accidental. In any case the remarkable integral multiple property of certain levels in B^{10} is not mentioned in the later review articles of the Pasadena group [4, 5, 6].

More information on the study of these energy levels in B^{10} will be quoted in paragraph 2. The levels considered have mainly been investigated by means of the $Be^9(d,n)B^{10}$ reaction. As the energy of the deuterons so far never exceeded 3.5 MeV, we decided to make a new study of the reaction mentioned above for 7 MeV deuterons.

The present investigation was started already before the deuteron beam of the small cyclotron at the Nobel Institute of Physics was deflected out of the acceleration chamber. It was then necessary first to study the energy and the homogeneity of the internal beam. The method used for this investigation is described in paragraph 3.

2. Earlier investigations of the low energy levels in B^{10}

It was mentioned above that in the level scheme of B^{10} the levels at about 1.4 and 2.9 MeV had been omitted in the later reviews by the Lauritsen group. Regarding earlier investigations, we start by quoting such works where one or both of these levels have been believed to exist.

In 1939 Haxel and Stuhlinger [7], using a slow-neutron threshold method on the $Li^7(\alpha,n)B^{10}$ reaction reported excited levels in B^{10} of 0.77, 1,32 and 2.09 MeV energy. The same reaction was studied by Robbins [8]. He used two independent methods, one of which consisted in the determination of the neutron energies by means of recoil protons from a hydrogenous radiator. The energies of the recoil protons were found from their range in aluminium. In the second method the reaction threshold for each level was determined with an enriched BF_3 counter. The experiments were performed with thin Li_2SO_4, LiB and metallic beryllium targets. The lithium in the Li_2SO_4 target was 99 % Li^7. Similar level structure was found in experiments with the various targets. The combined results of these investigations consisted in energy levels in B^{10} at excitation energies of 0.74, 1.31 and 1.72 ± 0.06 MeV. A comparative experiment with a Li^6 target was performed in order to test the assignment of the levels to B^{10}. Robbins points out that recent

Table 1. Some data for the excited levels $\lesssim 3.5$ MeV in B^{10}.

Author	Bombarding particles	Excited levels, MeV					
Haxel and Stuhlinger (1939)	3–8.8 MeV	0.77	1.32	—	2.09	—	—
Rasmussen, Hornyak, and Lauritsen (1949)	1.2 MeV *d*	0.713	1.424	—	2.138	—	3.580
Ajzenberg (1951)	3.436 MeV *d*	0.77	—	1.79	2.22	—	3.59
Reid (1954)	0.75 MeV *d*	0.62	—	1.83	2.21	2.88	3.49
Robbins (1956)	0–8 MeV	0.74	1.31	1.72	—	—	—
Génin (1958)	$\left.\begin{matrix}0.570\\0.695\end{matrix}\right\}$ MeV *d*	0.72	1.20	1.72	2.16	2.95	3.60

experimental investigations of the energy level structure of light nuclei indicate that certain levels are not observed in all reactions leading to the same final nucleus.

Reid [9] used a triple-coincidence, proportional counter telescope recording those recoil protons from a thin film of polythene which were projected in the same direction as the neutron beam from the $Be^9(d,n)B^{10}$ reaction. In addition to the well established levels he found a level at 2.88 MeV.

The same reaction was also studied by Génin [10] who confirmed the result of Reid and found the existence of a 1.20 MeV level probable. For the "2.85 MeV" level, however, Génin obtained the value of 2.95 MeV. The method used was the recoil of protons in nuclear emulsions.

Table 1 shows the results given above and the energy of the bombarding particles (d or α).

It is seen that there is an indication for levels at 1.4 and 2.9 MeV.

Besides the observations by Reid and by Génin, which indicate the existence of a level with an energy of about 2.9 MeV, a closer study of the neutron energy distribution curves of some earlier investigations of the $Be^9(d,n)B^{10}$ reaction supports the existence of this level. In order to show this, we reproduce these energy distribution curves of the recoil protons observed by Bonner and Brubaker [11] (Fig. 1*a*), Staub and Stephens [12] (Fig. 1*b*), Powell [13] (Fig. 1*c*) and Ajzenberg [3, 15] (Fig. 1*d*). Bonner and Brubaker determined the neutron energies by measuring the lengths of the recoil proton tracks in a high pressure cloud chamber filled with methane. The deuteron energy was 0.9 MeV. Staub and Stephens [12] measured the recoil proton energy in a cloud chamber of 15 cm diameter, using a deuteron energy of 0.6 MeV. Powell [13, 14] introduced photographic emulsions into nuclear physics. Using 0.5 MeV deuterons, he determined the energy of the recoil protons in nuclear emulsions using the expansion chamber results of Staub and Stephens. Ajzenberg [3] studied the neutron spectrum at 0° and 80°, and later [15] also at 10°, 30°, and 45°, using nuclear emulsions and 3.436 MeV and 3.39 MeV deuterons, respectively. The distribution curves in Fig. 1 are arranged so that neutron groups belonging to the same energy level in B^{10} are approximately one above the other. The groups marked A, B, C, D, E correspond to the ground state, the 0.72, 1.74, 2.15, and 3.58 MeV levels, respectively. It is obvious that in all distributions there are indications for a weak group between D and E, not just exactly half-way between D and E, but a little closer to E, corresponding to a level with an energy of about 2.9 MeV. A similar trace of a 2.9 MeV level is seen in the work by Whitehead and Mandeville [16], who used nuclear emulsions and deuterons of 1.62 MeV energy.

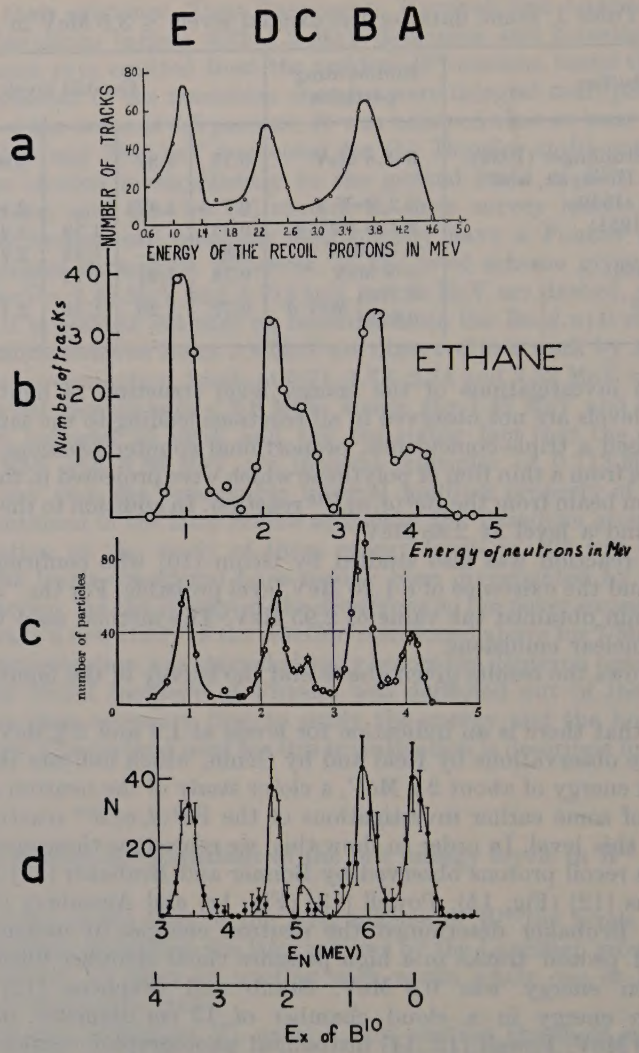

Fig. 1. Energy distribution of neutrons from the Be(d, n) B reaction. Results of (*a*) Bonner and Brubaker [11], (*b*) Staub and Stephens [12], (*c*) Powell [13] and (*d*) Ajzenberg [3, 14]. For discussion see the text.

Pruitt, Swartz, and Hanna [17] studied the angular distribution of neutrons from the $Be^9(d,n)B^{10}$ reaction, using 0.945 MeV deuterons and measuring the energy of the neutrons by means of nuclear emulsions. The same neutron groups as mentioned above were investigated for seven different angles between the direction of the deuteron beam and the direction of the velocity of the neutrons. The energy of the levels studied was found to be 0, 0.74 ± 0.11, 1.77 ± 0.10, 2.20 ± 0.10 and 3.67 ± 0.09 MeV. Also in this case a study of the recoil proton spectra given does not exclude the possible existence of a 2.9 MeV level in B^{10}.

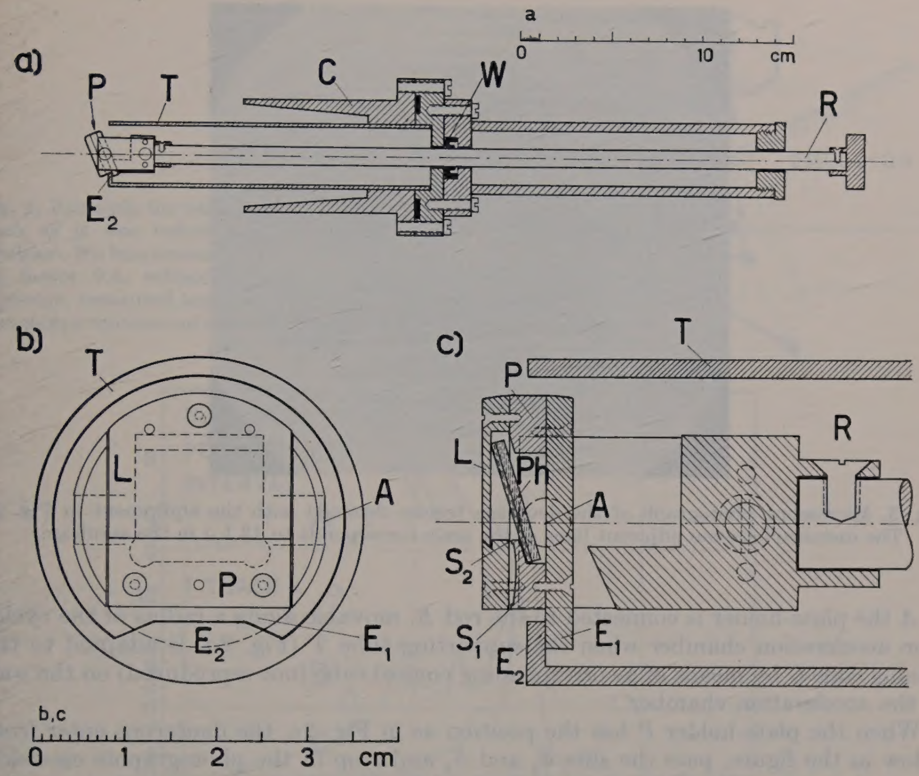

Fig. 2. Equipment for exposure of nuclear emulsions to cyclotron internal-beam particles (in the present case deuterons), drawn schematically. (*a*) Axial section of the equipment, consisting of a supporting tube *T*, joining cone *C* for connection to a conical tube of the cyclotron vacuum chamber, and a rod *R* for operating the plate-holder *P*. (*b*) Section through the plate-holder *P* at right angles to the tube *T*. (*c*) Section of the plate-holder *P* along the axis of the tube *T*. For details see the text.

3. Measurement of the energy distribution of the deuterons inside the cyclotron acceleration chamber

Already before the deuteron beam in the 7 MeV cyclotron of the Nobel Institute of Physics was deflected and taken out of the vacuum chamber, the possibility to study (d, n) reactions with internal Be-targets was considered. As such a possibility depended mainly on the energy homogeneity of the deuteron beam hitting the target, a device for a short duration, deuteron exposure of a small nuclear emulsion plate at the place of interest was constructed.

Fig. 2 shows diagrammatically this recording equipment for the ion tracks in the beam. A square nuclear emulsion plate 14×14 mm², Ph, is placed inside the plate-holder *P*, *L* being the cover of the plate-holder. Two slits S_1 and S_2 of about 20 μ in width permit the deuterons to hit the photographic plate Ph for a certain angular position (Fig. 2*c*) of the plate-holder which can be turned on the axle *A*. By means

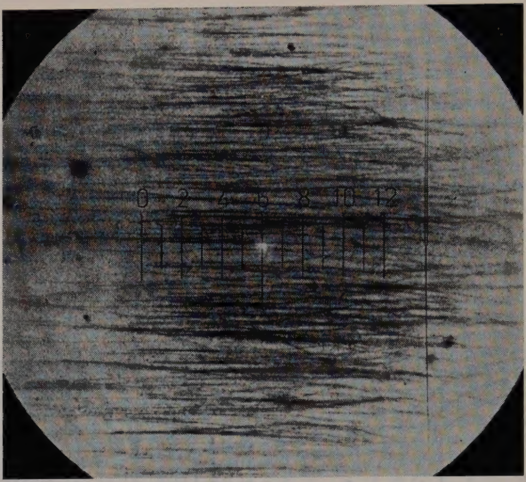

Fig. 3. Microscope photograph of the deuteron tracks obtained with the equipment in Fig. 2. The distance between adjacent lines of the scale corresponds to 13.1 μ in the emulsion.

of A the plate-holder is connected to the rod R, movable along a radius of the cyclotron acceleration chamber when the supporting tube T (Fig. 2*a*) is adapted to the joining cone C by means of a corresponding conical tube (not reproduced) on the wall of the acceleration chamber.

When the plate-holder P has the position as in Fig. 2*c*, the deuterons enter from below in the figure, pass the slits S_1 and S_2 and stop in the photographic emulsion layer of the plate Ph. This special position of the plate-holder occurs only for a time of the order of magnitude 10^{-5} sec, when the rod R is rapidly moved to the left in the figure.

In the initial position, when the plate-holder has been loaded, the angle between the plate-holder and the rod is adjusted to be $< 90°$, the rod R is drawn outwards (to the right in the figure) and thus the plate-holder put in a protected position close to the bottom of the tube T. The equipment is then connected to the cyclotron acceleration chamber, and this is then evacuated. The running of the cyclotron starts with a low beam intensity. As a matter of fact, it was necessary to take the photographs just after the arc in the ion source was broken in order not to get over-exposed emulsions. The exposure was made simply by pushing the rod R rapidly towards the interior of the acceleration chamber (to the left in the figure). When the edge E_1 (Fig. 2*c*) struck the edge E_2, the plate-holder rapidly passed the perpendicular position (Fig. 2*c*), in which the emulsion was exposed. Immediately after this the plate-holder reached an inclined position (as in Fig. 2*a*), making an angle with the rod $> 90°$. In order to protect the plate against further radiation, the plate-holder was then drawn outwards until it reached the protected position near the bottom of the tube T. The direction of the plate-holder was not changed during this last operation and thus no additional exposure made.

Fig. 3 shows a photograph of the deuteron tracks thus obtained and seen under a microscope equipped with a rotatable mechanical object stage, which permitted the linear parts of the tracks to be observed sharply along their whole length [18]. Fig. 4

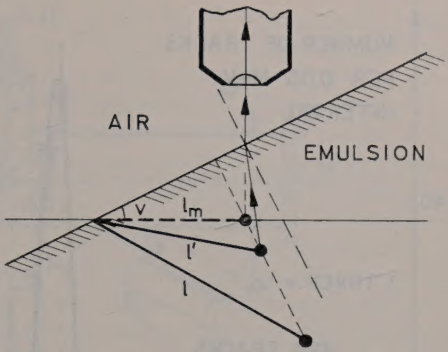

Fig. 4. Principle for calculating the length l of a track as it was before the development of the emulsion. No immersion oil. The emulsion shrinking factor 0.5, refraction index 1.5. l_m is the apparent, measured length of the track. The new microscope mechanical object stage [18] was used.

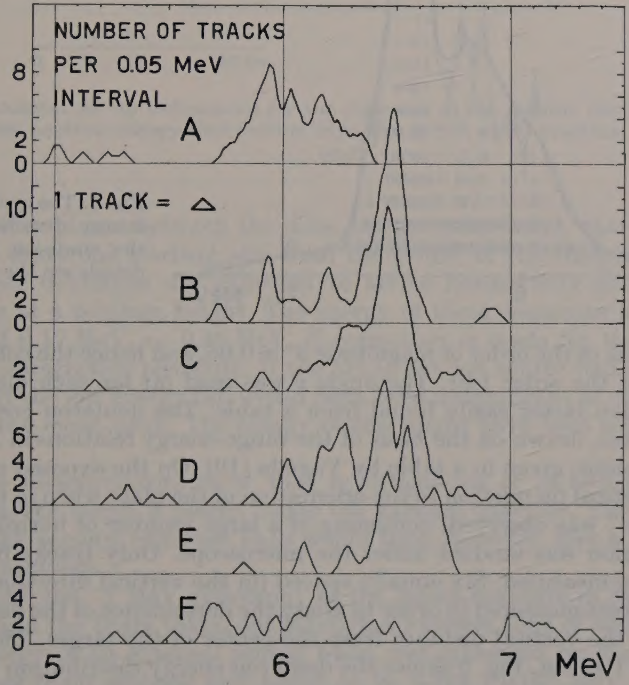

Fig. 5. Dependence of the cyclotron deuteron energy distribution on the vertical distance from the center of the internal target. For details see the text.

shows the principle for calculating the length l of a track as it was before the development of the emulsion. If l_m be the measured, apparent length of the track, the stage angle being v (= angle between the optical axis of the microscope and the normal to the surface of the emulsion), we have, in the case of no immersion oil, and if the emulsion shrinking factor is 0.5, refraction index 1.5,

$$l \approx \frac{l_m}{1 - 4 v^2}. \qquad (1)$$

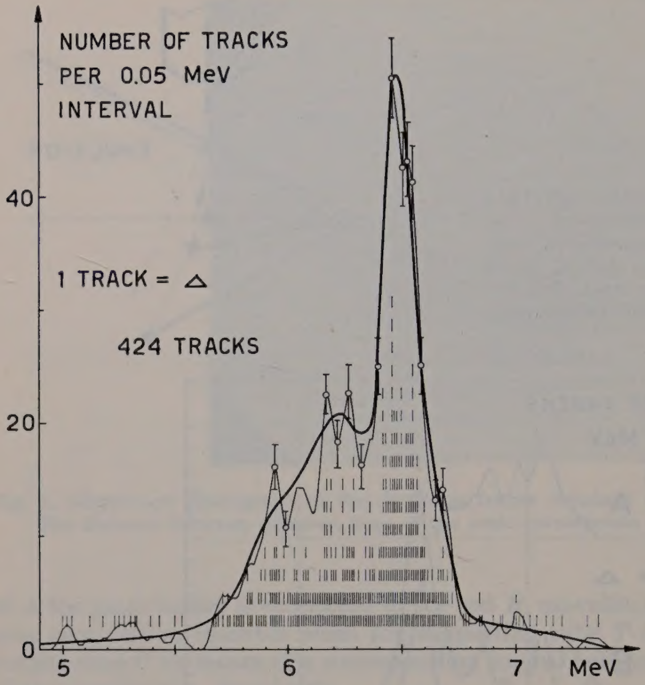

Fig. 6. The cyclotron deuteron energy distribution found by the emulsion technique. For details see the text.

The angle v was of the order of magnitude $3° \approx 0.05$, and hence the correction factor $1/(1-4v^2)$ was of the order 1.01. The angle v was read off for each measured track, and the correction factor easily found from a table. The deuteron energy was then found from curves, drawn on the basis of the range-energy relations in Ilford Nuclear Research Emulsions, given in a table by Yagoda [19]. On the exposed and developed small plate a vertical (in relation to the orientation of the plate when in the cyclotron), faint, grey "line" was observed, consisting of a large number of horizontal deuteron tracks. This region was studied under the microscope. Only tracks from the most dense areas were measured. Six equally spaced (in the vertical direction) areas *A*, *B*, *C*, *D*, *E* and *F* were measured in order to study the dependence of the deuteron energy distribution on the vertical distance from the center of the target. The total height of the area was 1.15 cm. Fig. 5 shows the deuteron energy distribution thus obtained for each investigated area and Fig. 6 the integrated distribution. The integration method used has been described earlier [20]. Fig. 6 shows a well defined peak at a deuteron energy of 6.5 MeV and, in addition, a broad tail of lower energy. The high energy peak does not appear in the distributions of the highest and lowest areas, *A* and *F* respectively, Fig. 5. On the other hand, these tail distributions are most pronounced in *A* and *F*. This fact indicates that the "tail deuterons" belong to excentric, oblique (not horizontal) paths, the centers of which are driven along small circles, having the ion source as a center. The drive is caused by the gradient of the magnetic field of the cyclotron. It is obvious that the tail is more pronounced owing to the special trick of exposing the photographic plate just after the arc in the ion source was broken. The effect of this method must be a reduced number of deuterons starting from the center of the vacuum chamber, compared with deuterons which

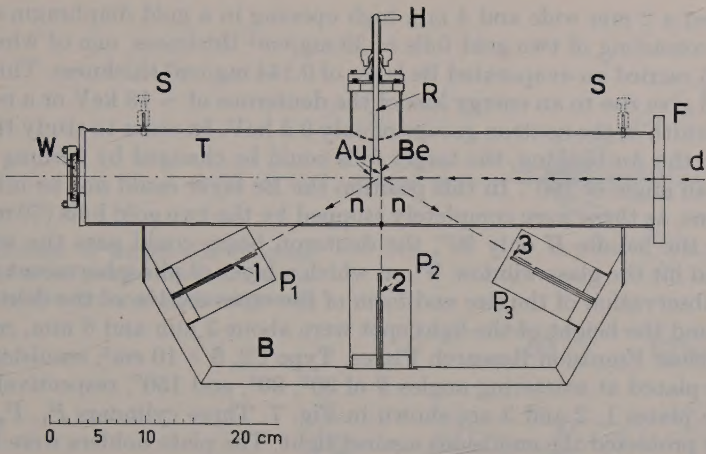

Fig. 7. Experimental set up (schematic) for the exposure of the nuclear emulsion plates used in the study of the neutron energy distribution from the $Be^9(d, n)B^{10}$ reaction. For details see the text.

start from other places between the dees. On the other hand, there is no reason to believe that deuterons starting also from the center of the chamber should not be present. These deuterons are expected to arrive horizontally and hit the photographic plate at a medium height. The energy of these deuterons is 6.5 MeV with a half-width of 0.17 MeV, or 0.16 MeV, if correction is made for the 0.05 MeV half-width of the integration elements. If the arc in the ion source had not been broken, it is clear that the low energy tail would have been insignificant as compared with the intensity of the mean peak. The energy of this might have been slightly higher, say 6.6 MeV.

The above measurements show that investigations of (d,n)-reactions might be possible when the target is placed inside the vacuum chamber. The large amount of material in the vacuum chamber walls would then, however, give a high background of scattered neutrons.

At this state, the "7 MeV cyclotron" at the Nobel Institute in Stockholm was reconstructed and the beam taken out through a vacuum tube of about 8 m in length [21]. The energy of an external proton beam was measured by Malmfors *et al.* [21] by the time-of-flight method and found to be 3.483 ± 0.007 MeV. The energy of a deuteron beam from the same cyclotron should thus be 6.97 MeV. As the strength of the cyclotron magnetic field was increased by a small amount during the reconstruction of the cyclotron, the new deuteron energy value found by Malmfors *et al.* and our earlier value found by the emulsion technique are not in disagreement.

4. Experimental arrangement. Exposure.

Fig. 7 shows diagrammatically the experimental set up used for the study of the $Be^9(d,n)B^{10}$ reaction. A thin-walled brass tube *T* (target chamber) of about 60 cm in length was connected by means of the flange *F* to the deuteron beam vacuum tube of the cyclotron. The deuterons entered the target chamber from the right in the figure, passed a 2 mm wide and 4 mm high opening in a gold diaphragm and hit the target *Au*, consisting of two gold foils of 35 mg/cm^2 thickness, one of which (the foil to the right) carried an evaporated Be layer of 0.144 mg/cm^2 thickness. This beryllium layer should give rise to an energy loss of the deuterons of ~ 13 keV or a contribution to the half-width of the neutron groups of only 9.5 keV. In order to study the neutrons arising from the Au backing, the target foils could be changed by turning the handle *H* through an angle of 180°. In this position the Be layer could not be influenced by the deuterons, as these were completely stopped by the two gold foils (70 mg/cm^2 Au). By turning the handle *H* only 90°, the deuteron beam could pass the whole target chamber and hit the glass window *W*, on which a layer of phosphorescent zinc sulfide permitted observation of the size and form of the cross section of the deuteron beam. The width and the height of the light spot were about 3 mm and 6 mm, respectively. 3 Ilford Nuclear Emulsion Research Plates, Type C2, 5×10 cm^2, emulsion thickness 100 μ, were placed at scattering angles ϑ of 30°, 90°, and 150°, respectively. Sections of the three plates 1, 2 and 3 are shown in Fig. 7. Three cylinders P_1, P_2, and P_3 of black paper protected the emulsions against light. The plate holders were held by the thin-walled brass tube frame *B*.

Two sets of exposures were made. In the first one the Be-target was bombarded with a beam of $\sim 0.8\,\mu$A deuterons for 30 minutes. In the second case a similar deuteron bombardment was used with the gold target in order to study the neutron energy distribution of the gold neutrons, which gave a high background in the low energy region ($E_n \lesssim 4$ MeV) of the beryllium neutron energy distribution.

The use of a thick gold backing for the thin Be-layer presupposes a large cross-section for the $Be(d,n)B$-reaction in comparison with the production of neutrons from the gold backing. Smith and Kruger [22] found the absolute neutron yield for several (d,n)-reactions, using 10 MeV deuterons on thick Au targets. The yields ranged in value from $(3.7 \pm 0.4) \cdot 10^{10}$ neutrons (sec) μA for Be to $(0.054 \pm 0.007) \cdot 10^{10}$ for Au. According to these investigations, the (d,n) cross-section for Be should be about 70 times that for Au.

In the present investigation the Be-layer had a thickness of 0.144 mg/cm^2. Thus, a gold backing of 10 mg/cm^2 thickness should give about the same number of neutrons as the Be-layer. When the deuterons have passed the 10 mg/cm^2 of gold, they have lost about 1 MeV in energy. At the same time, the cross-section for the $Au(d,n)Hg$ reaction has diminished. Thus for a thick gold target, in which the 7 MeV deuterons are completely stopped, the yield of the gold neutrons should be somewhat larger than the Be-neutrons. This is in agreement with the experimental results, as will be shown below.

5. Measurement of the neutron energy distribution

First, in order to test the origin of the background neutrons, a small region close to the center of the background plate 2 was investigated. The direction and the length of the proton recoil track projection on the surface of the emulsion were measured for each of 34 tracks in the region mentioned. Each track found was used, without any selection. Fig. 8 shows the result. The arrow *n* shows the direction from the gold target. It is seen that all recoil protons seem to be caused by neutrons coming from the target, as no backward- directed or 90°-deflected protons are observed.

So far only the "90° plates" (No. 2 in Fig. 7) have been studied. Such a plate was

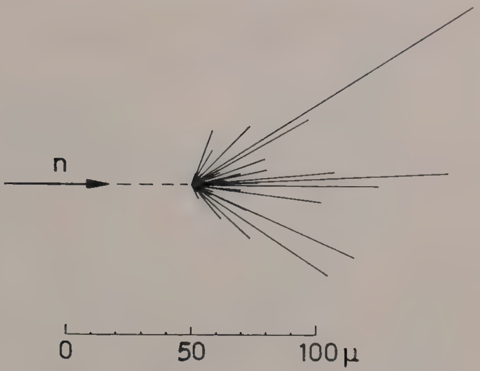

Fig. 8. Distribution of length and direction for each of 34 recoil proton tracks found in a small region of the center of the background plate No. 2.

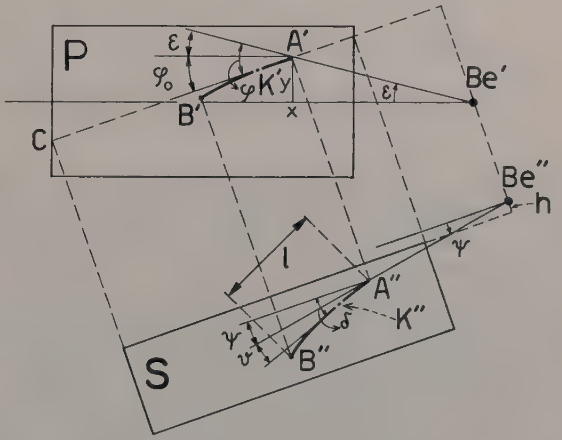

Fig. 9. Quantities of interest for the neutron energy calculation. *P*, plane of the emulsion. *S*, section through the emulsion, perpendicular to *P*. Be, neutron source. *A′B′* and *A″B″*, horizontal and vertical projections of the proton recoil track *AB*, respectively. In the old method (before introducing the new mechanical object stage) a point *K* on the track *AB* was chosen in order to measure the directions of the tangent to *AB* in *A*.

placed with its emulsion center 150 mm from the target and with the emulsion surface making an angle of about 0.9° with the direction from the target. Thus, the angle ϑ between the direction of the motion of the neutron and that of the deuteron will not be exactly 90° for all parts of the plate. However, in calculating the Q-values of the $\mathrm{Be}(d,n)\mathrm{B}$ reaction, the maximum error in Q caused by using $\Theta = 90°$ will be about ± 0.02 MeV for a single track, and hence of no importance for a mean Q-value computed from several tracks belonging to the same excited level.

Because of the poor yield of recoil protons found in the emulsions, it was necessary to use also recoil protons making angles up to about 20° with the direction of motion of the neutrons. The deviations φ in the plane of the emulsion are easier to measure accuractely than the deviations v in directions perpendicular to the emulsion plane. It was therefore decided to use recoil protons for which $|\varphi| \leqslant 20°$ and $|v| \leqslant 10°$.

Fig. 9 shows diagrammatically the quantities of interest for the neutron energy determination. P is a projection of the emulsion on the photographic plate and S a projection of the emulsion on a plane perpendicular to the plate P and cutting the line $A'C$, $A'C$ being the tangent to the projection $A'B'$ of a proton recoil track AB (A is the starting point, B the end point). Be' is the projection of the source Be of the neutrons. The figure 9 is not drawn to scale. Be was situated at $h = 2.4$ mm over

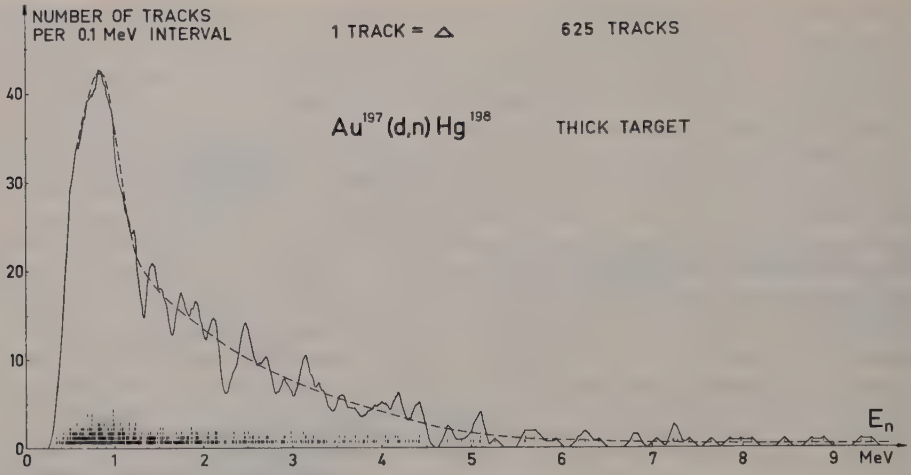

Fig. 10. Energy distribution of the neutrons from a thick gold target.

the plane of the emulsion and 150 mm to the right from the midpoint of the plate. The coordinates x, y, the angles φ_0 and $\delta = v + \psi$, as well as the length l of the track, were measured directly under the microscope by means of the new mechanical object stage described elsewhere [18]. The angles ε and ψ were computed for different x, y values and easily obtained from a graph. As a matter of fact, ψ depends also on φ_0. However, the maximum value of ψ was 1.3°, and as the maximum value of φ_0 was about 27°, (maximum deviation $\varphi = \varphi_0 + \varepsilon = 20°$, $\varepsilon = -7°$), the maximum φ-depending variation of ψ was $1.3°(1 - \cos 27°) = 0.14°$. Because this angle is of the same order of magnitude as the accuracy of the depth angle measurement, it was neglected, (such an error in the determination of the angle v causes a maximum error in the neutron energy of only 0.01 per cent). The depth of the point A under the surface of the emulsion was not considered for the computation of ψ, as the thickness 0.1 mm of the emulsion was small in comparison with $h = 2.4$ mm. ψ was put equal to $h/A'Be'$.

The energy E_p of the recoil protons was obtained from the well-known range-energy relations for Ilford Nuclear Research Emulsions [23], and then the energy E_n of the striking neutron found from the simple formula

$$E_n = E_p/\cos^2 v \cos^2 \varphi. \tag{2}$$

For the plates in the position 2, Fig. 7, ($\vartheta = 90°$), the Q-values were computed by means of the formula

$$Q = E_n\left(1 + \frac{M_n}{M_r}\right) - E_d\left(1 - \frac{M_d}{M_r}\right), \tag{3}$$

where M_d, M_n and M_r are the masses of the deuteron, the neutron and the B^{10} nucleus, respectively. For E_d the value 7.00 MeV was used.

Fig. 10 shows the energy distribution of the background neutrons, arising from the thick gold target. The distribution curve indicates a predominant number of

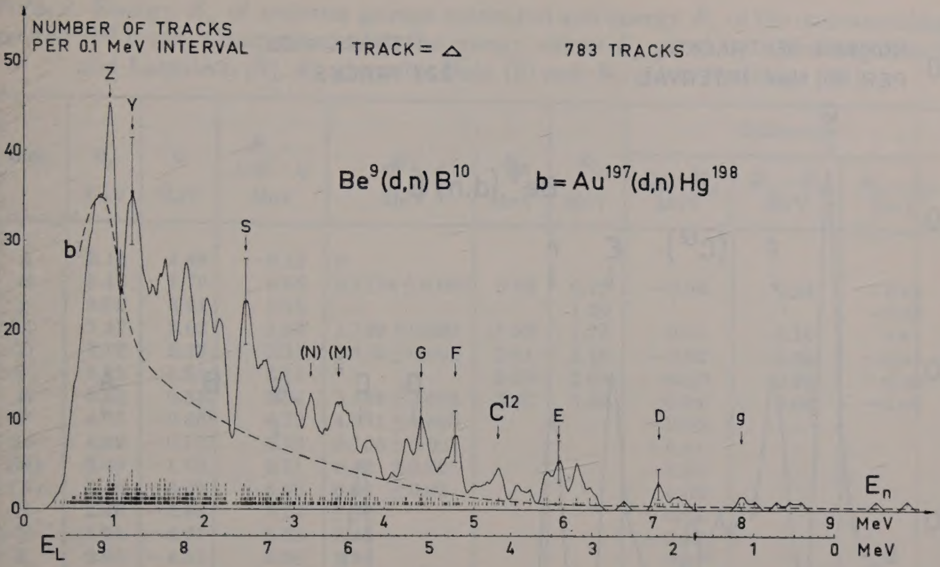

Fig. 11. Energy distribution of the neutrons from the Be-Au target. b = gold neutron background estimated with the aid of Fig. 10. E_L = energy scale for the excited levels in B^{10}.

neutrons having an energy of about 0.8 MeV. However, as the very short tracks were not measured, the true shape of the distribution curve for energies lower than about 0.7 MeV is not known. Most of these neutron energies were obtained from recoil protons, the tracks of which were measured in "the old manner", which was used before the new microscope mechanical object stage [18] was constructed.

At that time two angles of depth, δ and δ', had to be measured. In order to get $\delta = v + \psi$ (Fig. 9), the depths h_A and h_K (not marked in the figure) of the points A and K under the surface of the emulsion were measured. The depth angle δ was then computed from the difference $h_K - h_A$ and the length of the projection $A'K'$. In order to get the length l of the track AB, the depth h_B of the endpoint B of the track had also to be measured. The angle δ' of the chord $A''B''$ with the emulsion surface was then obtained from the difference $h_B - h_A$ and from the distance $A'B'$. The length l of the track was then considered to be $l = A'B'/\cos \delta'$. As the magnification of the microscope was 1250, the lengths of the tracks usually had to be measured in many steps. It is obvious that this older method is not only more laborious but also less accurate than the new one, which is based on the mechanical object stage [18]. However, the result obtained for the continuous background neutron energy distribution should not be much different from a result based on the more accurate method, as no sharp lines are to be expected in connection with thick targets.

Fig. 11 shows the energy distribution found for the neutrons from the Be-target ($\Theta = 90°$). Almost all (592) of the 783 tracks are measured by means of the old method. b is the estimated gold neutron background. Obviously, the background is too large for a satisfactory study of Be-neutron groups with energies below 4 MeV. It was therefore decided that, in the following only those tracks for which $E_n \gtrsim 4$ MeV would be measured.

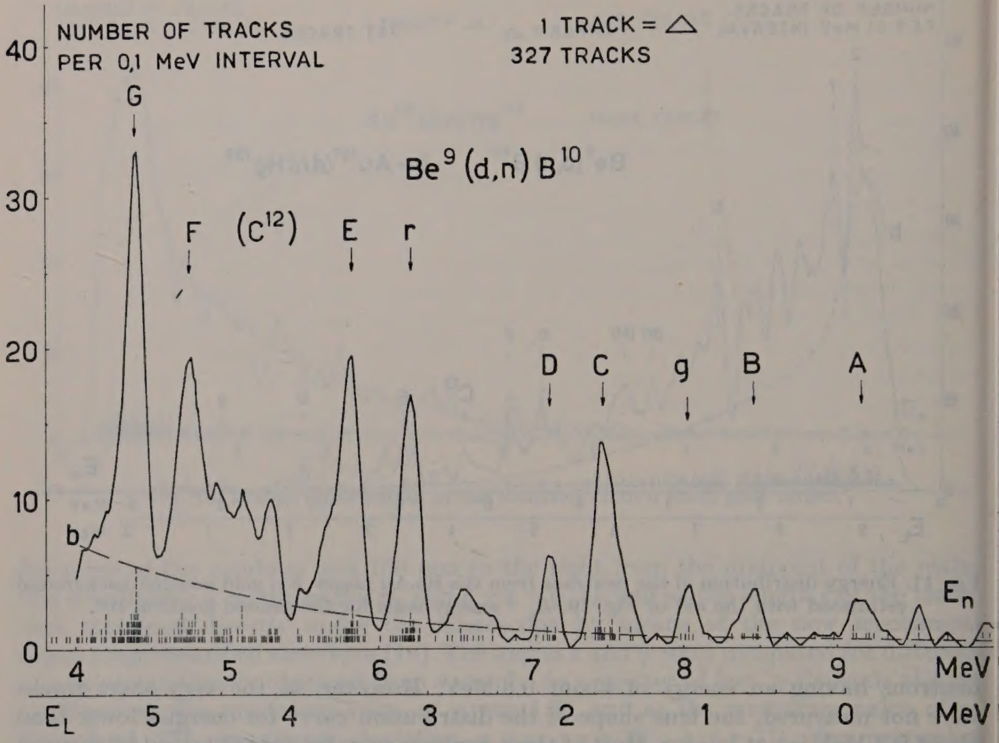

Fig. 12. Energy distribution of the neutrons from the Be(d, n)B reaction. b = gold neutron background, estimated with the aid of Fig. 10. Only neutrons for which $E_n \gtrsim 4$ MeV, have been considered. E_L = energy scale for the excited levels in B^{10}. For details see the text.

The energy values for the neutron groups observed are listed below (Table 2).

Fig. 12 shows the energy distribution of the neutrons for which $E_n \gtrsim 4$ MeV. The corresponding recoil proton tracks have been measured by means of the new microscope mechanical object stage [18]. It is obvious that the neutron energy lines now appear to be much more sharp and clear cut than the lines obtained with the old method. The line G, for instance, has a half-width of only 135 keV.

The energy distributions in Figs. 10, 11, and 12 are not corrected for the finite emulsion thickness, nor for the differing probability of impacts for different neutron energies.

6. The energy levels of B^{10}

Table 2 shows the result obtained for the Be(d,n)B reaction.

It is seen that the energies E_L of the excited levels agree to within 0–37 % of the half-widths of the lines (these being about 0.16 MeV) with the corresponding lines given by Ajzenberg-Selove and Lauritsen [6]. The E_L values were computed by means of the formula (3). The value 4.36 MeV is the abbreviated value $Q_m = 4.358$ MeV for the ground level Q-value of the Be(d,n)B reaction given in ref. 6.

Table 2. Energy E_n of neutron groups measured and energy E_L of the corresponding excited B^{10}-levels. Comparison with the energy values E_A given by Ajzenberg-Selove and Lauritsen [6], E_R given by Reid [9] and E_G given by Génin [10].

Line	E_n MeV	Q MeV	$E_L = 4.36 - Q$ MeV	E_A MeV	E_R MeV	E_G MeV	Difference		
							$E_L - E_A$ MeV	$E_L - E_R$ MeV	$E_L - E_G$ MeV
A	9.15	4.48	−0.12	0					
B	8.45	3.70	0.66	0.7174±0.001	0.62	0.72	−0.06	0.04	−0.06
g	8.02	3.24	1.12			1.20			−0.08
C	7.47	2.63	1.73	1.739±0.005	1.83	1.72	−0.01	−0.10	0.01
D	7.12	2.23	2.13	2.152±0.005	2.21	2.16	−0.02	−0.08	−0.03
r	6.21	1.25	3.11	*	2.88	2.95	(0.1)*	0.23	0.16
E	5.82	0.82	3.54	3.583±0.005	3.49	3.60	−0.04	0.05	−0.06
F	4.75	−0.36	4.72	4.771±0.005			−0.05		
G	4.39	−0.76	5.12	5.105±0.007			+0.01		
(M)	3.49	−1.75	6.11	6.16 ±0.02			−0.05		
(N)	3.18	−2.09	6.45	6.40 ±0.03			0.05		
S	2.46	−2.88	7.24	7.20			0.04		
Y	1.25	−4.27	8.63	8.66			−0.03		
Z	0.95	−4.54	8.90	8.89			0.01		

* According to ref. 3, Fig. 1, and ref. 15, Fig. 7, of which a part is reproduced in the present work, Fig. 1 d, a line "r" at $E_A = E_X = 3.0 \pm 0.2$ MeV should not be in disagreement with *Ajzenberg's* measurements.

7. Discussion

The present investigation confirms the results of Reid [9] and Génin [10], who found a level with an energy of 2.88–2.95 MeV in the level scheme of B^{10}, even though our value is higher, 3.1 MeV. It is pointed out that tracks of this line are found in the Be(d, n)B reaction neutron energy distribution diagrams presented by some other authors.

The existence of the line g is possible but cannot yet be proved because of insufficient statistics.

The use of a higher deuteron energy gives a different intensity ratio for the neutron groups than for lower deuteron energies. Thus, in the present investigation, the Reid–Génin line *r* is prominent.

The high background of gold neutrons for lower energies prevented a study of the higher B^{10}-levels. It is intended to make a new exposure with an improved target in order to be able to study the corresponding low energy neutron groups.

In the study of the neutron energies by measuring the recoil proton tracks in nuclear emulsions the new microscope mechanical object stage [18] was found to be very useful. The measurements were performed with higher accuracy and in a shorter time than before. As large deviations of the direction of the track from the direction of the velocity of the bombarding neutron as ± 20° in the plane of the emulsion and ± 10° in a plane perpendicular to the emulsion plane permitted the recording of neutron energy distributions, in which the half-widths of neutron groups were of the order of magnitude of 0.13–0.20 MeV.

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